PLASMA CONTROL OF FLOW SEPARATION ON SWEPT WING AT HIGH ANGLES OF ATTACK

A.D. Budovsky, B.Yu. Zanin, I.D. Zverkov, V.V. Kozlov, A.A. Maslov, B.V. Postnikov, A.A. Sidorenko

Khristianovich Institute of Theoretical and Applied Mechanics SB RAS, 630090, Novosibirsk, Russia

1. Introduction

It is well known that flow separation leads to the dramatic changes in aerodynamic characteristics of the aircrafts. Thus the ability to manipulate a separating flow to effect a desired change is of great practical importance.

This paper deals with plasma flow control applications, namely, control of boundary-layer separation on swept wings at high angles of attack using surface plasma discharges.

Attempts to manipulate and ultimately control separation over stalled airfoils have typically relied on narrow-band receptivity of separating flows to external periodic actuation. Separation is simultaneously affected by two instability mechanisms: local instability of the separating shear layer and, more importantly, instability of the wake that ultimately leads to the formation and shedding of large-scale vortical structures into the wake flow [1]. The problem of boundary-layer separation control perfectly fits into the rapidly growing area of plasma flow control [2].

This paper discusses new applications of dielectric barrier discharge (DBD) to flow separation control on swept wings with microsecond DBD’s in a large subsonic wind tunnel test environment. It is well known, that DBD is able to introduce not only desired periodic disturbances, but also one is able to produce periodic flow acceleration in the boundary layer region [3], and thus, it can lead the boundary layer velocity profile to become more filled. These features make it possible to use DBD for solving the task of boundary layer separation control.

2. Experimental Setup

The experiments were performed in the low-turbulence subsonic ITAM T-324 wind tunnel with the parameters: velocity range from 3 to 50 m/s, square test section 1m×1m×4m. The freestream disturbances of this facility are well documented. This is important for interpretation of unsteady separation phenomena playing critical role in the stall physics. The turbulence intensity, $Tu = 0.04\%$, is small that facilitates extrapolation of wind-tunnel data to flight conditions.

The experimental model has been prepared for wind tunnel experiments. It is swept wing with sweep angle 25° with chord $c = 0.331$ m and span $l = 1$ m (see photo in Fig. 1). The airfoil used for the model is RAE5212 transonic airfoil of 12% thickness. This airfoil is a classical transonic one and was used for many experimental studies and CFD verifications. Experimental data and computational results concerning characteristics of RAE5212 are available in literature. This airfoil has all typical features of modern transonic airfoils. The model has 50 pressure lines and can be equipped with the same number of pressure taps. The most of pressure measurements were done in centreline of the wing, $z = l/2$ where $l$ is wing span. In some test cases 1 or 2 pressure taps on suction surface of the model were covered by electrodes and pressure data at those points were not available. The direction of pressure taps line is normal to leading edge. The airfoil shape and positions of pressure taps are presented in Fig. 2. The model was placed horizontally in the test chamber and secured.

Fig. 1. Photo of the swept wing model
© A.D. Budovsky, B.Yu. Zanin, I.D. Zverkov, V.V. Kozlov, A.A. Maslov, B.V. Postnikov, A.A. Sidorenko
in turning wall supports so the angle of attack can be changed during run of the wind tunnel. The design of DBD is similar to one used in most studies devoted to DBD flow control [4, 5].

Electrodes for DBD were made from adhesive aluminium film of 50 μm and were placed along the whole leading edge of the model. Encapsulated electrode has 7 mm in width; the other was glued 1 mm overlapped and has 7 mm in width too. The barrier was made from three layers of PVC adhesive film and has 240 μm in total (Fig. 3).

Further we will consider the downstream edge of exposed electrode as the “DBD position” $\tilde{x}$. The overlap decreases local thermal shock for PVC exposed to intensive heating at electrodes boundaries. Parasitic capacitance of such electrode configuration was 370 pF.

A.A.Lab Systems Ltd. AN-1003 hot-wire anemometry system was used to measure velocity distributions near the model and obtain velocity pulsation spectra. Self-made data acquisition system based on National Instruments PCI boards was used for data collection and pre-processing.

The one-component traversing gear was adopted for using in the experiments. It allowed us to move and position the hot-wire probes with accuracy of 0.01 mm in any section in the neighbourhood of the model. The control of the stepping motor is integrated in the data acquisition system. The traverse gear could be installed at any desired position on the test section walls by means of magnet support.

Surface pressure distributions were measured by means of multi-column manometer. Such system as multi-column manometer coupled with CCD camera was found to be very simple, fast and reliable instrument. Settling time of manometer is about 3-4 seconds, which is acceptable for our tests. The manometer was photographed by CCD camera and image of 2048x1536 pixels was processed by Image Recognition Software PAMIR to get numerical values of $P_{th}$, $P_{st}$ and surface pressures $P_r$. Resolution of pressure measurement system is 10 Pa. Image recognition software PAMIR was written and adopted to use together with 50-channel column manometer. The software is able to acquire images from CCD camera and save data as space distribution of pressure coefficient $C_p$.

3. High-voltage equipment

The portable DBD power supply (HVG) was developed for our experiments. HVG is 220V AC powered device and ready be powered by for 12V DC. It was optimized for effective operation (about 5-7% internal loses) in frequency range 500 Hz ÷ 5 kHz. But it can be operated in range...
from 20 Hz to 100 kHz with some minor modifications. Powered by HVG, DBD discharges up to 10 m long, 300 W at the gap with 10 min operation time can be initiated.

Voltage and current pulses were measured by means of two-channel 60 MHz TDS 2002 and four-channel 200 MHz TDS 2024B Tektronix oscilloscopes, 75 MHz Tektronix P6015A high voltage probe, 60 MHz Tektronix P6021 current probe. Example of high voltage and current 1600 Hz pulses measured are shown in Fig. 4. Voltage amplitude is about 5-6 kV and current peaks are about 0.2 A.

HVG also can operate in burst mode (Fig. 5), when it starts formation of pulses at frequency $f$, driven by internal or external generator, which sweep high-voltage packages initiated with low frequency $F$ when voltage at “START” HVG input is above some value. In our experiments sinus voltage of 10 V peak-to-peak initiates burst mode with frequency $F$ (Fig. 6). Duration of the high-voltage package depends both on $F$ and sinus wave amplitude. If the latter was constant and we varied $F$ from 5 to 100 Hz then electric power calculated at the gap was constant and equal 30 W for all $F$ with 5% accuracy, as with increase of $F$ the package duration decreases. High-voltage package exists during approximately 80% of positive sinus semi period duration.

4. Experimental Results

A. Preliminary investigations

Several series of wind tunnel tests were performed in T-324 ITAM wind tunnel. First of all it was necessary to obtain information about flow around the RAE5212 airfoil. We have performed set of tests for airfoil without DBD actuators to get an idea about mean flow and flow pulsation, position of the separation bubble, stall angle of attack and etc.

Samples of oil-flow visualization prints of the flow over the model for attached ($U_\infty = 50$ m/s, $\alpha = 5^\circ$), partially-separated ($U_\infty = 44.7$ m/s, $\alpha = 12^\circ$) and full-separated ($U_\infty = 44.7$ m/s, $\alpha = 18^\circ$) flow regimes are presented in Fig. 7a,b,c correspondingly. It was found, that on suction side of the airfoil the separation bubble formed even for small $\alpha$ in tested velocity range. It is easy to see from Fig. 7a that separation bubble exists on the downstream part of the wing (one can see the separation as well as the reattachment lines) and the width of separation region here is about 17 mm. The width of separation bubble region on the upstream part of the wing is about 18 mm. Since the wing is swept, further we will use the following terms with analogy to ones used to describe geometry of backward-swept wing aircraft: wing root – the upstream part of the wing; wing tip – the
downstream part of the wing.

Fig. 7. Oil-flow visualisation of the flow near wing tip:

a – $\alpha = 5^\circ, U_\infty = 50$ m/s (view from upstream)
b – $\alpha = 12^\circ, U_\infty = 44.7$ m/s (view from upstream)
c – $\alpha = 18^\circ, U_\infty = 34.7$ m/s (view from downstream)

The separation and reattachment lines on the whole wing are clear to see so we can conclude that separation bubble extends along the whole leading edge of the model and looks two-dimensional, but slightly narrowing to wing tip. In this case the boundary layer downstream of the bubble is turbulent and attached if $\alpha$ is small enough. As angle of attack increases the bubble moves upstream and at some moment the flow begins to separate in wing tip/wall corner (downstream part) forming the separation region. This region is growing with increasing of $\alpha$ and extends in direction to wing root (upstream part). The separation in this case looks like as global one which means that the flow separates from the leading edge and does not reattach. Only separation line can be found in oil-flow print in this case on the half part of the wing (see Fig. 7b). And finally, when $\alpha$ reaches its critical value the whole surface of the wing (up to wing root) is occupied by the separation zone (Fig. 7c).

B. Experiments with 2D DBD actuators

Several kinds of DBD actuator positions, configurations and excitation voltage variants were studied. We mainly focused on investigation of mechanism of flow pulsation excitation by DBD. For this purpose we have done experiments with DBD actuators placed along the leading edge. The position of DBD and direction of plasma zone were varied. Effect of voltage amplitude, frequency and modulation was studied.

Actuator upstream of separation bubble

The DBD actuator for this case was placed at $\tilde{x} = 9$ mm from the leading edge, upstream of separation bubble aroused along the leading edge and extends over all span of the model. This means that DBD was upstream of global separation line if the flow was separated. Pressure coefficient was calculated by the following formula for experimental data:

$$C_p = \frac{P_s - P_{st}}{P_0 - P_{st}}$$

Fig. 8 and Fig. 9 present experimental data obtained for DBD position upstream of the separation bubble. This data were obtained for free stream velocity close to maximum value for wind tunnel $U_\infty \approx 44$ m/c, $\alpha = 16^\circ$. The effect of DBD activation is seen from video frames of tuft visualization (Fig. 8) and from pressure distribution graphs (Fig. 9). Flow visualization allows us to get an idea about 3D structure of separation on the surface of the swept wing. Local pressure distributions are affected by the whole flow structure. Combined analysis of both of these data contributes to better understanding of the flow.
It can be seen from Fig. 8a that if DBD is off, the flow above the right (wing tip) half of the wing is separated. When DBD was activated the zone of attached flow suddenly expanded (Fig. 8b).

![Fig. 8. Video frames (α = 16°, U∞ = 43 m/s)](image)

The curve of pressure distribution for the case DBD is off (Fig. 9) looks like corresponding to attached flow regime. It is so because the most of pressure taps are very close (or inside) to zone of attached flow. At the same time, the curve corresponding to the moment of activated DBD (Fig. 8b, Fig. 9) shows re-distribution of pressure and increasing of suction peak near the leading edge. The effect of flow reattachment is not so obvious from pressure distributions, but tuft visualisation shows that the flow reattaches on considerable part of the wing.

With increasing of the angle of attack the initial separation zone is gradually enlarging and occupying the whole wing up to wing root. It can be seen form Fig. 10a that for \( \alpha = 17^\circ \) the separation occupies \( \frac{3}{4} \) of the wing. In this case all pressure taps are in the separation region of the model for “DBD off” regime. Therefore the curve corresponding to the “DBD off” regime in Fig. 11 is so typical for stall pressure distribution. Activation of DBD results in sudden reattachment of the flow on the most part of the wing apart from wing tip / wall corner (see Fig. 10b).

![Fig. 10. Video frames (α = 17°, U∞ = 43 m/s)](image)

The separation in this corner presents almost for all combinations of \( U_\infty/\alpha \) except when value of \( \alpha \) is very low and connected with wing/wall interference. The curve for the “DBD on” case in Fig. corresponds to reattached flow (see also Fig. b) and indicates re-distribution of pressure due to flow reattachment. Some pressure taps were covered by electrodes and are not plotted in graphs.
Fig. 12a and Fig. 12b demonstrates an effect of DBD excitation frequency on efficiency of reattachment. It is possible to see that low frequency excitation (f < 1 kHz) was not very effective and the flow remains separated at least on half of the wing (Fig. 12a). This result is probably connected with selective receptivity of separation to frequency of pulsations or low power of DBD for these frequencies. If DBD was excited with frequency 1 ÷ 2 kHz the flow reattachment was achieved on the most part of test model as shown in pressure distributions (Fig. 12b). Increasing of excitation frequency above 2.2 kHz up to 3 kHz results in decrease of control efficiency and the flow remains separated, nevertheless higher power in discharge. It is necessary to mention that for “continuous mode” excitation the average power is increasing with frequency.

![Graph for Fig. 11: Midspan pressure distribution (α = 17°, \( U_\infty = 43 \text{ m/s} \))](image1)

Fig. 11. Midspan pressure distribution (\( \alpha = 17^\circ, U_\infty = 43 \text{ m/s} \))

![Graph for Fig. 12: Midspan pressure distribution (\( \alpha = 18^\circ, U_\infty = 43 \text{ m/s} \))](image2)

Fig. 12. Midspan pressure distribution (\( \alpha = 18^\circ, U_\infty = 43 \text{ m/s} \))

![Graph for Fig. 13: Midspan pressure distribution, DBD off (\( n = 300 \text{rpm} \))](image3)

Fig. 13. Midspan pressure distribution, DBD off (\( n = 300 \text{rpm} \))

Fig. 13a and Fig. 13b show continuous changes of mid-chord pressure distribution for one run of wind tunnel. In these cases rotation speed of wind tunnel fan was kept constant and corresponded

Section II
to 43 m/s for $\alpha = 18^\circ$. The angle of attack was continuously increased. Data were obtained for test cases: “DBD on” and “DBD off”. It is possible to see that in Fig. 13a there is increasing of LE pressure peak up to $\alpha = 16^\circ$ and gradual decrease of it then $\alpha$ increases farther. It means that separation zone arose in wing tip region and gradually expands to wing root as $\alpha$ increases. If we do the same for activated DBD (Fig. 13b), the separation develops in different way. The flow resists to separation up to critical value of $\alpha = 19^\circ$ and suddenly separates after that on the whole wing.

**Actuator downstream of separation bubble**

The important question is: what is the main mechanism of separation control by DBD. The existent experimental data on airfoil separation control by acoustic waves give an idea about possible analogy in case of DBD. It is well known that discharge streamers of DBD propagating through the air radiate sound waves. In this case sound radiation can be a competitor of direct force production for the role of main mechanism of flow control. Unfortunately, it is not possible isolate one of these mechanisms. Instead of that we can place the DBD in such zone that direct force production effect will be neglected. In present study we placed DBD in position inside separation bubble ($\bar{x} = 24$ mm form the leading edge). The location of the separation bubble does not change too much with increasing of $\alpha$, so the actuator remained inside for all studied flow regimes. At the same time, its position is very close to separation line for stall regime and we may assume that acoustic dumping is moderate.

Experiments were performed in wide range of flow parameters, but the effect of flow reattachment was achieved only for very narrow envelope ($\alpha = 10^\circ$, $U_\infty = 10$ m/s). This envelope corresponds to low values of flow speed and angle of attack. Due to the fact that the flow reattaches only on 1/3 of model span near wing root, the pressure distribution in mid-chord position remained unaffected. Thus the fact of reattachment is proved only by tufts visualization. As a quantitative criterion of DBD efficiency in this case we assume the number of tuft columns which were affected by attachment of the flow.

![DBD OFF](image1)

![DBD ON](image2)

**Fig.14. Video frames ($\alpha = 10^\circ$, $U_\infty = 10$ m/s, $f = 1200$ Hz)**

Photos in Fig. 14 – Fig. 15 shows video frames corresponded to this test case. Figures “a” show tuft visualization for initial flow, figures “b” – for flow with activated DBD. It can be seen, that initially about 2/3 of the wing span was occupied by the separation zone. When DBD was activated the left border of the separation region moves to wing tip. The size of separation region in this case depends on DBD frequency. Fig. 14b shows that for DBD frequency 1200 Hz only 2-3 tuft columns indicate attachment of flow.
Increasing of frequency results up to 1550 Hz in stronger effect, 4 tuft columns are attached in Fig. 15b. If the frequency of excitation was further increased, the effect become weaker (same as one presented in Fig. 14b) and remains almost constant with increasing of frequency up to $f < 2500$ Hz. DBD excitation with frequency of 2500 Hz demonstrated the same effect as one presented in Fig. 15b. Further $f$ increasing led to decreasing of flow control efficiency again. These experiments were repeated several times and results showed good repeatability.

Additional test was made having in mind acoustic nature of the DBD effect. The model was exposed to strong acoustic radiation of variable frequency from loudspeaker driven by sine generator. For the same flow conditions ($\alpha = 10^\circ$, $U_\infty = 10$ m/s) it was found that flow reattaches. For maximum available acoustic power we have obtained the same value of effect as for excitation by DBD. The strongest effect was found for $f = 1550$ Hz. Thus we can conclude that there is very weak acoustic way of separation control by DBD. In this case the second maximum for $f = 2500$ Hz is due to non-harmonic nature of high-voltage generator.

**Burst mode of DBD excitation**

The initial idea of application of “burst mode” for DBD feeding was to keep the average power constant versus frequency. This regime was possible to set only for low burst frequency $F < 100$Hz. The position of DBD in this test was $\tilde{x} = 4.5$ mm downstream of the leading edge. To create bursts of high voltage the main frequency $f = 1600$ Hz was modulated by rectangular signal of burst frequency $F$ which was varied in range of $1 \div 100$ Hz. The relatively low flow speed was chosen for this test to keep Strouhal number of the burst excitation $St = Fc/U_\infty$ about 1.
It was found that for some flow regimes the excitation in “burst mode” is more effective than continuous one. Fig. 16 shows comparison of pressure distributions obtained in burst and continuous \((f = 1600\, \text{Hz})\) modes. It can be found that size of the separation zone decreases and pressure peak increases as \(F\) reaches value of 100 Hz. The distributions for burst mode \(F = 100\, \text{Hz}\) and continuous mode are very similar for \(\alpha = 16.5^\circ\) and \(U_\infty = 14.9\, \text{m/s}\). If the angle of attack was increased up to \(17.5^\circ\) the burst mode was found to be the most efficient one (Fig. 17). It is necessary to say that a pressure distributions show only averaged values of pressure. It is so due to long pressure lines and nature of the equipment used for experiment. More detailed information about temporal features of the flow was obtained by means of hot-wire anemometer.

Fig. 18 demonstrates vertical profiles of mean velocity and RMS value of velocity pulsations for DBD excitation in burst mode. An example of DBD voltage oscillogram for this case is shown in Fig. 6. These data were obtained at \(z = 330\, \text{mm}\) from wing root, for \(U_\infty = 11\, \text{m/s}\) with “DBD off” and “DBD on” regimes. Data were averaged through 4 seconds and are presented for various frequencies \(F\). Average time was limited by time of DBD activation (about 5 minutes for the whole profile) and not enough to have smooth profiles for separated flow. It can be seen that the flow remains attached if DBD on and separates if DBD off. When DBD on, the flow reattaches and remains attached for all time of DBD activation. It is interesting to see that frequency \(F\) affect the shape of profiles. The higher \(F\) the thinner boundary layer and smaller value of RMS pulsations near the wall. It is necessary to remember that these profiles represent time averaged data.

To analyze temporal behavior of the flow lets have a look on time histories of velocity presented in Fig. 19 for \(F=100\, \text{Hz}\). The oscillograms are not synchronized to each other so phase shift between them is possible. Comparison of these data with velocity profiles presented in Fig. 18 allows us to conclude that for excitation in burst mode there is some kind of intermittency of separated and attached flow. Particularly, it is interesting to see from Fig. 19 that at a distance of \(Y=2\, \text{mm}\), local velocity value oscillate near average one at this point and reach minimum value that is similar to that corresponding separated boundary layer and maximal value that considerably exceed average velocity in the case of completely attached flow at the distance. Therefore we can see higher lift for burst mode shown in Fig. 17. Such flow behavior is seen from all the data presented (Fig. 19). Dependence of boundary layer velocity profile shape from burst frequency \(F\) is likely explained by the fact that duration of attached flow pattern do not concur with duration of DBD duty cycle. It means that the flow reattaches during the duty cycle of DBD and separates again not instantaneously at the end of duty cycle when DBD is off but with some time delay, that can be named as separation relaxation time \(T_{\text{sep}}\). Correspondingly the higher \(F\) the separation is less developed. Thus it can be supposed that boundary layer velocity profile will be more filled if
\( T_{\text{rep}} \leq T_{\text{sep}} \), where \( T_{\text{rep}} \) – pulse packet repetition cycle. Due to this fact we can see dependence of mean velocity profiles in Fig. 18. The increase of wing lift obtained for burst mode (Fig. 17) in comparison to attached flow regime is probably accompanied by periodic pressure loadings.

Fig. 19. Oscillograms of velocity in the separated zone for “burst mode” excitation \((F = 100 \text{ Hz})\)

5. Conclusions

Research of separation control on the model of swept wing with transonic airfoil was carried out at subsonic speed with chord Reynolds number \( 0.3 \div 1.3 \times 10^6 \). Dielectric barrier discharge plasma on the surface of the model was used for separation control. Effects of the angle of attack of the model, discharge frequency, location and geometry of discharge actuators were studied in experiments. It was found that DBD can be successfully applied for separation flow control on the swept wing at high angle of attack. The experimental results show that variations of DBD location, power and frequency have significant effect on the separation control efficiency and mitigation of the separation region. The most effective was DBD placed near the leading edge upstream of separation line. The possibility of acoustic mechanism of boundary layer turbulence was studied. It was found that acoustic radiation from DBD weak and can not be considered as main mechanism of separation control. It was shown that DBD operated in burst mode can be more effective for separation control. In this case activation of DBD not only mitigates the separation but it can promote to increase the wing lift.

REFERENCES